



Online impedance spectroscopy of lead acid batteries for storage management of a standalone power plant

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H I G H L I G H T S

- ▶ The power converter excites the battery for impedance spectroscopy at any working point.
- ▶ Measurement of AC voltage and current in battery thanks to an automatic calibration.
- ▶ PWM frequency and sample frequency are linked to reject noise.
- ▶ Impedance spectroscopy is performed by the control system without additional power hardware.

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This paper presents a contribution to implementation of hybrid power plants in rural areas without electricity in Senegal. Wind and photovoltaic generators coupling is used to benefit from renewable energy resources in this country. Lead acid storage batteries are coupled with the generators to ensure smoothness of the electricity generation. This work is focused in particular on the development of a low cost online impedance spectroscopy method to address the problem of limited lifetime of batteries and the difficulties of their maintenance in isolated areas. Control of static converter associated with the battery is adapted to integrate the functionality of characterization of batteries by impedance spectroscopy. An experimental platform developed in the laboratory has validated the method for online measurement of battery impedance spectrum and to initiate a phase of data monitoring.

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1. Introduction

The energy needs of humanity significantly increase today given the massive industrialization, population growth and the recent development of certain geographical areas. Energy consumption jumped by 49% over 25 years (1980–2005). This energy used each day in the world comes in large part of raw material that is extracted from the ground (oil, gas, coal and uranium): fossil and nuclear energies.

Unfortunately, these energies have a harmful impact on the environment and the health of the populations. Their use requires budgets bigger and bigger because of soaring prices and their abuse as is the case now caused it to disappear sooner than expected. The use of renewable energy should be a priority, especially in

developing countries where energy from fossil fuels represents 90% of energy consumption and is a very important budget item. For a country like Senegal, which has a significant renewable energy potential, the use of alternative energy sources will allow a greater number of people to access to development. It will result in wealth creation and will limit the country's dependence on foreign energy resources. Recent wind measurement campaigns (2004–2009) between Saint-Louis and Thies have revealed a potential of average wind up to 6 m s^{-1} and gusts exceeding 10 m s^{-1} at heights between 20 and 40 m. Solar resource is very high everywhere in Senegal, with a daily average insolation of 5 kWh m^{-2} and a sunshine duration of more than 3000 h per year.

This project involves studying the establishment of a few kilowatt multi generators consisting of a wind turbine, a photovoltaic source and a storage system feeding a DC bus. This is a contribution to strengthening the use of renewable energy in the country. The implementation of technological solutions based on autonomous hybrid generators using renewable energy can be an early solution

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to the continuous energy deficit of Senegal. Autonomous stationary power supplies, coupling several renewable energy sources and means of storage, are attractive to power small communities living in remote areas. Indeed, the construction of power lines to connect remote areas to the network can cause a very significant additional cost.

The efficiency of electricity production in isolated areas is sensitive to maintenance difficulties due cost constraints or unavailability of equipment or personnel. This problem concerns especially the electrochemical storage battery whose lifetime is short compared to other components and depends on the conditions of use. This paper proposes a particularly low cost solution to help maintain storage batteries.

After describing the topology of the autonomous power plant and the operating principle of each component, we present control methods leading maximum recovery of solar and wind, and the principle of storage and release of energy. We will then discuss the description of characterization methods of storage batteries and in particular impedance spectroscopy method. Then, we describe the implementation strategy of impedance spectroscopy into the power converter control. Finally we present the experimental results of online characterization of a battery before concluding.

2. Architecture of the Central

Wind and photovoltaic generators and storage batteries are coupled through static converters to a common DC network as shown in Fig. 1. The converters are defined to ensure the conversion of the shape and amplitude of currents and voltages and allow adjustment of the operating point of the sources. The DC network is connected to a capacitive bridge sized to achieve adequate stability of the DC voltage whose mean value is defined with respect to the voltage level required by the electrical power supply (typically a DC voltage of 540 V is required to power a 230 V AC network with a three-phase inverter). This average value must be maintained in a margin of about $\pm 10\%$ by acting on power transfer in batteries. This will preserve the ability of the power plant to feed the power grid by the inverter.

The adjustment of the operating points of wind and photovoltaic generators is required to maximize energy recovery. Indeed, the turbine speed for which maximum power is recoverable depends on wind speed. Thus optimizing energy recovery requires the control in variable speed of the wind turbine. It is here coupled

to a multiplier and an asynchronous generator which has the advantage of being well adapted to the constraints of mechanical robustness, low cost and low maintenance which are predominant in this project. The generator is coupled to a DC network by an AC/DC Pulse Width Modulation (PWM) converter. Regarding photovoltaic panels, the maximum recoverable power depends mainly on the conditions of insolation and temperature. The DC/DC boost converter allows the load characteristic to be adapted to these conditions and so the operating point can be adjusted to maximize the electrical power extracted to match to the maximum power point.

Energy storage by lead acid batteries has been selected for this project because of the affordability of this technology and its availability on the market better than newer technologies. A switching DC/DC converter adjusts the energy transfer between the DC network and batteries. The association of the battery cells is defined to maintain a boost operating mode of the power converter. The voltages at the batteries and photovoltaic panel terminals are selected to maintain a rising factor small enough to not damage the efficiency of the boost converters.

3. Management and storage of energy

3.1. Principle of optimization of energy recovery

The operating points of the wind and photovoltaic generators are adjusted from direct methods whose main asset is to get rid of measurements of external variables such as wind speed or insolation intensity. The principles of control of the wind turbine and photovoltaic panels are based on Perturb and Observe method [1] and a fuzzy controller respectively [2]. These methods are now well known and reliable and therefore will not be presented in this article. They enable the wind and photovoltaic energies to be optimally recovered by maintaining the operating point of the generators around the higher power operating point (MPPT method: Maximum Power Point Tracking) [3]. In the case of the wind turbine, the operating point is adjusted by acting on the speed reference and thus the torque by vector control of the induction machine fed by the AC/DC converter. The power supplied by the asynchronous generator is determined based on electrical variables. In the case of photovoltaic panels, the operating point is adjusted by acting on the current directly by acting on the duty cycle of the coupling DC/DC converter. The power supplied by the

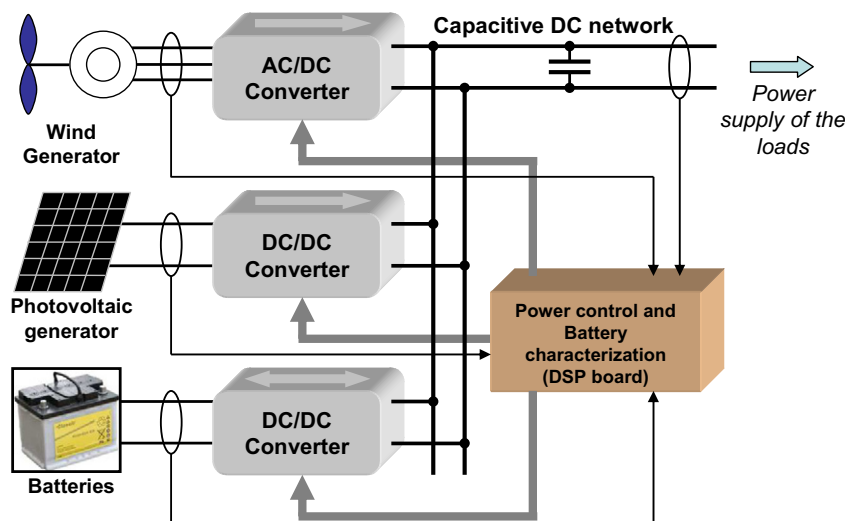


Fig. 1. Architecture of the wind and photovoltaic power plant.

photovoltaic panels is determined from the measurement of their current and the voltage at their terminals.

3.2. Control principle of energy storage in the battery

The batteries enable service continuity of the power plant. They perform storage of excess energy when the power production exceeds the power consumption or supply the energy requirement in the opposite case. Charging and discharging phases of the batteries depend on the sizing of the sources and profiles of wind, sunlight and power consumption. Fig. 2 shows the power consumption profiles estimated for a day (Fig. 2a) and over a year (Fig. 2b). It corresponds to the power consumption of a small group of houses and averages about 45 kWh per day.

The adjustment of the power balance is achieved by regulating the DC network around its nominal voltage. This feature is assigned to the static converter connected to the battery. This converter, shown in Fig. 3a is a bidirectional boost converter. The control is performed by two PI (Proportional Integral) correction loop which help regulate the DC voltage while controlling the current exchanged between the battery and the DC network as shown in Fig. 3b. The current profiles in the battery are then related to the profiles of wind, sunlight and consumption.

Thus, depending on the level of battery charge, we can define three main modes of management of energy flows:

- Mode 1: continuous operation. The batteries have an intermediate state of charge (SoC). MPPT algorithms are turned on and enable an optimal energy recovery from wind and photovoltaic generators. The excess or deficiency of energy to power the load is then directed to the batteries as defined by the following equation:

$$P_{\text{batteries}} = P_{\text{wind}} + P_{\text{PV}} - P_{\text{load}} \quad (1)$$

- Mode 2: maximum SoC of batteries achieved. The batteries are fully charged and available power is greater than the power required by the load: The power recovered is adapted by

disabling the MPPT algorithms. No power is delivered to the batteries.

- Mode 3: minimum SoC of batteries reached. The maximum depth of discharge of the batteries is reached and the power required by the load is greater than the power supplied by wind and photovoltaic generators: all or part of the load is unloaded according to the priority level of the consumers.

4. Characterization methods of batteries

4.1. Interests of characterization

Storage batteries are definitely components of shorter lifetime of the power station. Their aging depends firstly on operating conditions that are related to energy availability, the nature of the load and the control strategy and secondly external conditions, particularly temperature, which reaches high values in the proposed area. In these regions characterized by low material resources, low funds and scarce skilled personnel, the implementation of low cost solutions enabling the extension of the lifespan of batteries and assistance to their maintenance would significantly increase the reliability of the power plant and cost effectiveness in the medium term. Thus we present here a method to characterize batteries as an online process that will assess its SoC and state of health (SoH) without human intervention or expensive hardware. This tool will help to enhance knowledge of battery behavior in actual operating conditions and to consider acting on the architecture of the power plant, on its size and its control in order to improve its lifespan.

4.2. The main characterization methods of batteries

The advantage of characterization methods of batteries is to determine state indexes. The main state indexes of batteries are:

- The SoC defined for a temperature T as being the ratio between the capacity (C_s) and the rated capacity (C_n) of the battery. The rated capacity is obtained by applying a rated discharge mode

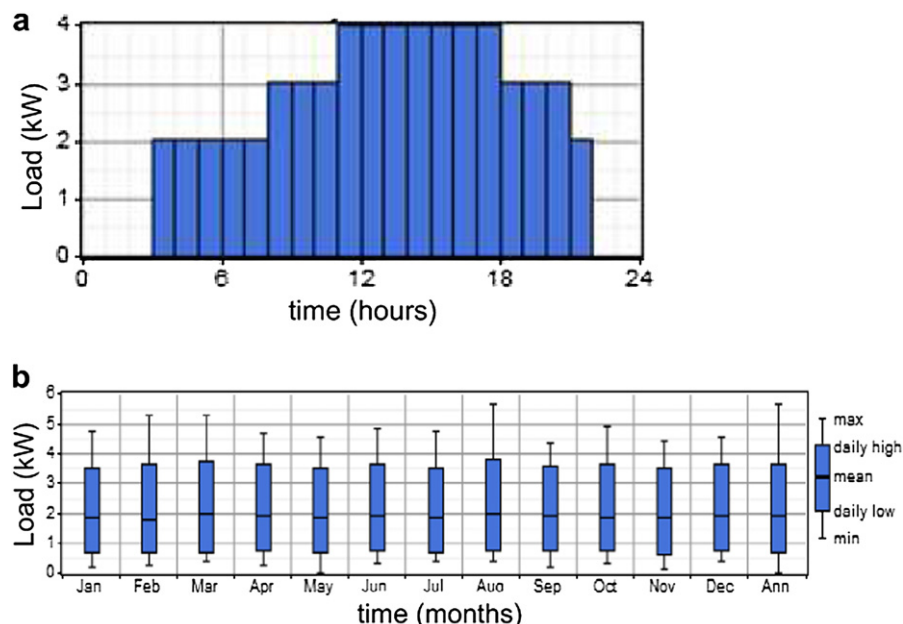


Fig. 2. Power consumption profiles. (a) Daily. (b) Annual.

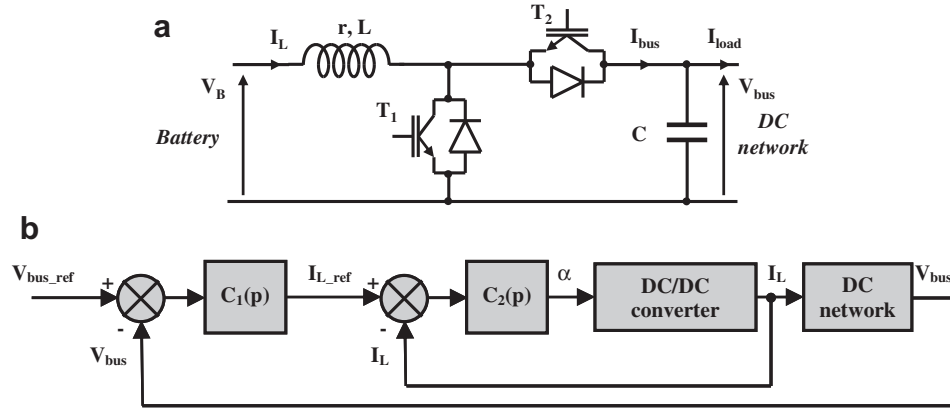


Fig. 3. Coupling of batteries. (a) DC/DC coupling converter. (b) Control principle.

under respect of the initial and final manufacturer's charge criteria [4].

$$SoC(T) = \frac{C_s(T)}{C_n(T)} \quad (2)$$

- The SoH defined as the ratio between the current rated capacity and the rated capacity of the battery when it was new [5]. Capacities are expressed for the reference temperature:

$$SoH = \frac{C_n}{C_{n0}} \quad (3)$$

Among the existing characterization methods [6–9], we can mainly retain:

- Energy counting: it allows battery SoC to be evaluated but losses are not precisely quantifiable, unless you know the battery internal parameters which may themselves vary over time.
- Measurement of the open circuit voltage of the battery at rest: also assesses the battery SoC but is approximate and has the disadvantage of requiring a relatively long period of rest before measurement.
- Measurement of the concentration of the chemical solution: also provides information on the battery SoC but the implementation of this measure requires an access procedure to the chemical solution impractical in operation.
- Battery impedance spectroscopy: provides information on the general state of the battery (SoC and SoH) according frequencies under consideration in the impedance spectrum. It requires to have a spectroscopy device and to make a Nyquist representation.

Due to the limitations of the first three methods and their difficulty of implementation, we opt for the measurement of the impedance spectra of batteries. The integration of the battery impedance spectroscopy to the system as an online process avoids periods of downtime and human intervention. It also minimizes the cost of implementation of the method by eliminating the use of sophisticated equipment, and benefits from the dynamic performances of the static converter and of their controller. The challenges are then to exploit the possibilities of static converter and extract the relevant content of the measures necessary to emulate a device capable of performing impedance spectroscopy of the batteries.

4.3. Battery impedance spectroscopy

The impedance of a battery can be modeled as the equivalent circuit shown in Fig. 4a also called Randle model [10,11]. Resistance

R_c is the ohmic resistance of the connectors. In the general case, its value is low and can be neglected. The resistance R_e characterizes the conductivity of the electrolyte. Phenomena that occur near the electrodes are characterized by the capacity C_{dl} linked to the double layer phenomenon, the resistance R_{ct} linked to the charge transfer phenomenon and the Warburg impedance Z_w linked to the diffusion phenomena induced by the production and consumption of elements at interfaces. The Nyquist diagram of the equivalent impedance is shown Fig. 4b. It enables the main parameters of the model of Randle to be graphically extracted and allows their variation around reference values to be assessed.

5. Integration of impedance spectroscopy process in the control of the power converter

5.1. Integration strategy of impedance spectroscopy in the power management

The impedance spectroscopy functionality is integrated into the converter coupling the batteries. The principle is to control the duty cycle of the power converter to create an excitation current in the batteries and simultaneously measuring the excitation current and voltage response to derive the impedance of the batteries for the excitation frequency under consideration. Using this principle for

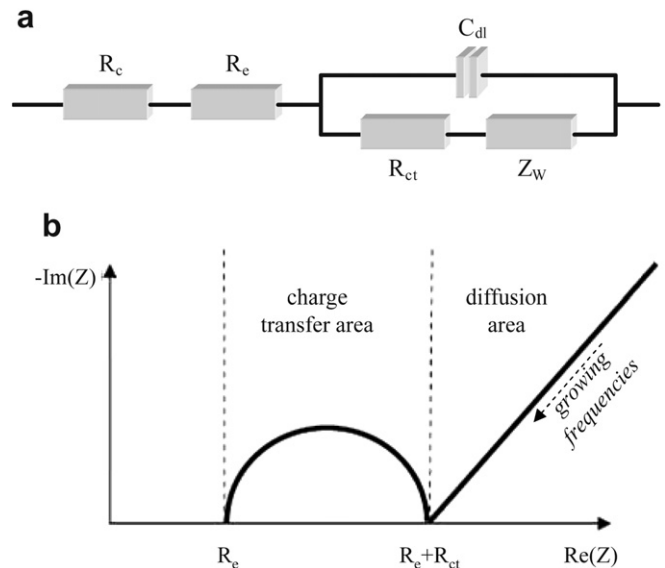


Fig. 4. Randle model of a battery. (a) Equivalent circuit. (b) Typical Nyquist diagram of the complex impedance of the model.

different frequencies chosen to cover accurately enough the relevant spectrum width will provide the Nyquist diagram of the battery impedance. Randle's model not being linear, the measurement of a full impedance spectrum must be done by small excitation signals around a fixed operating point in order to be usable [12]. Thus the implementation of the impedance measurement requires first of all maintaining of the batteries at a fixed operating point (i.e. a constant current I_0 in the batteries) for the entire duration of the measurement, and therefore disabling the control of the DC network voltage. The amplitude of the excitation signals of the batteries will remain small compared to their nominal magnitude to stay within the linear domain of the impedance model.

The process of impedance spectroscopy can be conducted online only if this particular mode of operation does not disrupt the continuity of service of the power plant. The hold of battery current at a constant value different from the value imposed by the power control mode involves a variation of the DC network voltage limited by the capacitive nature of the DC bus. Different strategies can be adopted as appropriate:

- The DC network voltage remains within the limits and its variations do not significantly disturb the value of current I_0 in batteries: impedance spectroscopy can be completed.
- Voltage variations of the DC network are not acceptable: it is then possible to temporarily suspend the impedance spectroscopy process and to reactivate the control of power transfer. Another option would be to disable the MPPT algorithms while the measurement of impedance spectrum to assign to static converters related to wind and photovoltaic generators the function of voltage control of the DC network.

These strategies are defined according to the dynamic characteristics of the plant and will not be detailed in this article which is focused on the principle of impedance spectroscopy. However, this behavior highlights the benefit of reducing the duration of the impedance spectroscopy process.

Fig. 5 illustrates the different phases of implementation of the impedance measurement of batteries by impedance spectroscopy.

The operating point for which the battery impedance spectroscopy has to be performed is first achieved by disabling the automatic control of the DC network voltage and forcing the

current in the batteries to the value I_0 by control of current only. When the current I_0 is reached, the current control is disabled to keep the duty cycle of the static converter at the last value α_0 characterizing the desired operating point, but also to avoid interference with the current excitation of the batteries during the process of impedance spectroscopy. At this stage, maintaining the DC network voltage is no longer provided by the converter coupling the batteries but one of the methods described above can be applied to address this problem. The impedance measurement is then performed for each frequency of the spectrum taken into account and finally the converter coupling the batteries resumed the control of the DC network voltage.

5.2. Analog calibration of measures

For a given state of charge, the battery model is assimilated to an electromotive force E_{bat} in series with the impedance Z_{bat} as shown in Fig. 6. The excitation current $I_{bat}(f)$ of the batteries at the frequency f and voltage response $V_z(f)$ are of small amplitude compared with mean values of current and voltage.

The harmonic impedance measurement requires the extraction of AC components of the current in the batteries $I_{bat}(f)$ and the voltage at the terminals of the impedance of the batteries $V_z(f)$. The impedance at frequency f of the battery is defined by:

$$Z_{bat}(f) = \frac{V_z(f)}{I_{bat}(f)} \quad (4)$$

These quantities are not directly accessible. Their digitization with precision is only possible after calibration of gain and offset of the total current in the batteries and the total voltage at battery terminals, which are physically measurable. The electronic calibration is controlled by the microcontroller to adjust gains and offsets to the operating point of the batteries and to impedance value. Fig. 7 shows the principle of interconnection of the electronic calibration with the microcontroller unit. The adjustment of the gains and offsets is performed using digital to analog converters (DAC) controlled via a Serial Peripheral Interface (SPI Interface).

Fig. 8 shows the simulation result of the calibration of the current I_{bat} to bring the measurement of its AC component I_{bat_alt} within the full scale measuring range [0; 3.3 V] of analog to digital converter (ADC) integrated into the microcontroller. The calibration

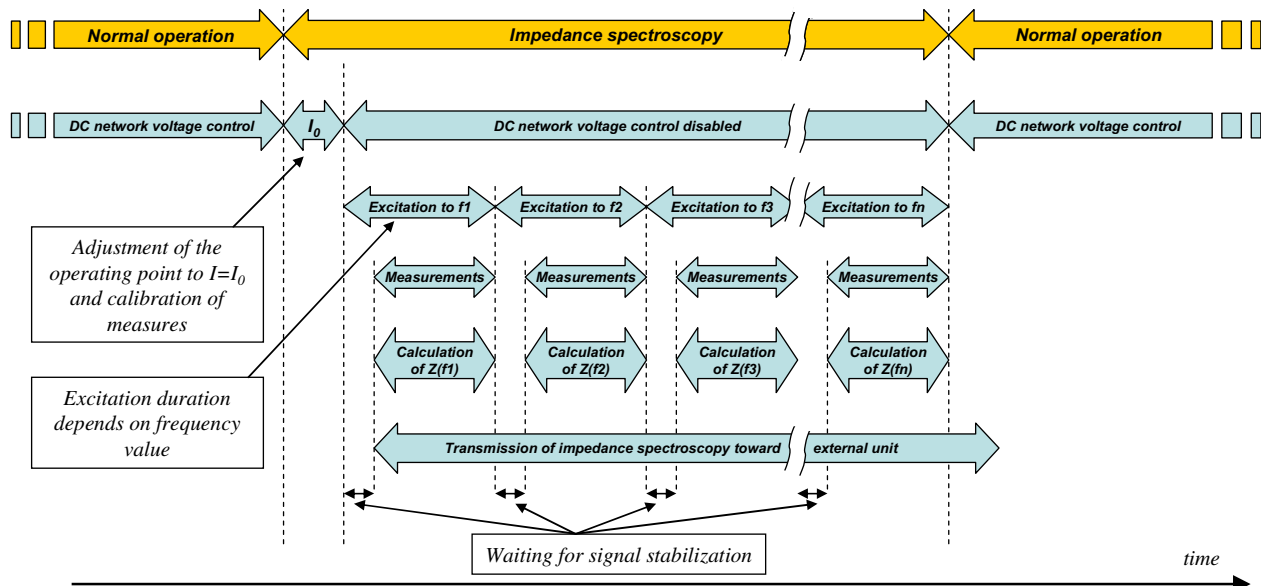


Fig. 5. Principle of integration of impedance spectroscopy to power transfer.

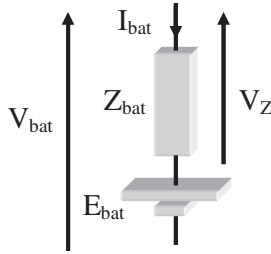


Fig. 6. Principle of measurement of battery harmonic impedance.

of the measurement of the excitation current and of voltage response is achieved during the phase of adjustment of the operating point of the battery characterized by the current I_0 . When calibration is complete, it must be disabled during the impedance spectroscopy process to avoid disturbing measurements.

5.3. Principle of excitation of the batteries

The principle of excitation of the batteries consists in imposing an alternating current $I_{bat_alt_ref}$ around the current I_0 using a control loop shown in Fig. 9. This method allows frequency and amplitude of the current excitation to be controlled, while remaining within the linear range of the considered model. The calibrated measurement of the current in batteries is the feedback of the control loop of the excitation current. The output of the controller defines the duty cycle variation around the value α_0 determined to achieve the desired operating point. The successive change of the frequency of the reference signal allows the relevant spectrum width to be scanned. The number of periods of excitation is set to establish a compromise between the required accuracy taking into account the possible residual noise before digital processing, the computational load, and the measurement time of the spectrum. The low-frequency harmonics have the largest contribution in the total duration of the measurement.

5.4. Principle of impedance measurement

The current in the battery is imposed by the static converter and therefore has a significant harmonic rate caused by the PWM switching as illustrated on the oscilloscope records of the battery current and voltage shown in Fig. 10. Current excitation is fixed in this example to a frequency of 2 Hz and an amplitude of $\Delta I = 0.4$ A around a mean value of $I_0 = 2$ A. These harmonics, whose amplitude depends on the switching frequency and the inductance of the converter, occur naturally in the measures after calibration of the excitation current and of its voltage response. The pseudo-Fourier series development of the signal shows that its spectrum consists of a main harmonic at the switching frequency F_{PWM} and harmonics groups of lower amplitudes placed on both sides of the switching frequency. These harmonics have frequencies spaced by a multiple of the excitation frequency (which is the modulating frequency of the static converter). The accuracy of measurement of the spectral components useful for impedance spectroscopy can be significantly affected by the disturbances due to switching of the converter.

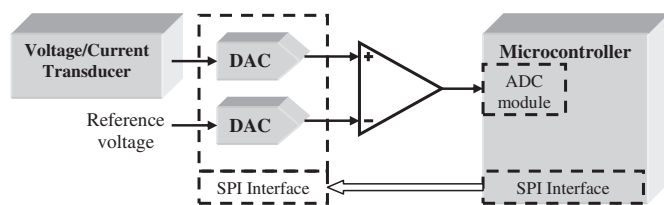


Fig. 7. Principle of electronic calibration.

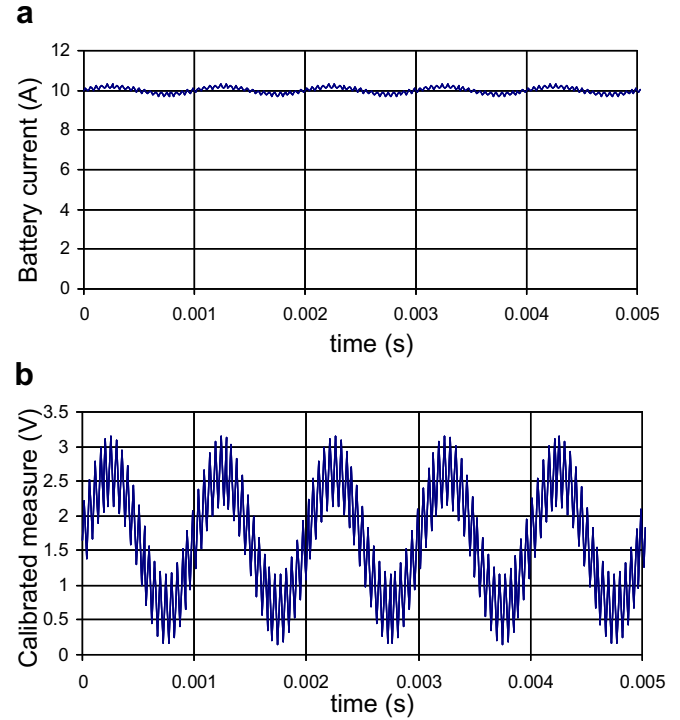


Fig. 8. Simulation example of calibration. (a) Battery current. (b) Calibration of the AC component in the ADC range [0; 3.3 V].

Indeed the amplitude of the harmonics created by the cutting of the current are not negligible compared to the amplitude of the excitation signals necessary for the battery impedance spectroscopy.

Fig. 11 shows the filtering principle which consists in providing a partial anti-aliasing analog filtering removing harmonic frequencies above the Nyquist critical frequency $F_e/2$ where F_e is the sample frequency. A residual component at the PWM frequency may persist at the filter output given the high amplitude of the disturbance at this frequency before filtering. The aliasing of this component is then locked onto the frequency axis zero by synchronizing the sampling frequency with the switching frequency ($F_e = F_{PWM}$). This method eliminates interference caused by switching of the converter regardless of its switching frequency and facilitates the design of anti-aliasing filters. Thus the spectral component f_i of the excitation can be easily extracted from the digitized signal which consists of this single component and a possible DC component. The principle is the same for the voltage response to current excitation.

The amplitude and phase of the excitation current and of the voltage response are then extracted from sampled signals by Discrete Fourier Transform (DFT). This treatment allows in particular a very good accuracy on the phase and amplitude even in case of disturbances in the unfiltered frequency area. The N samples of a signal allow the real and imaginary parts of harmonic of rank k to be computed. The rank of the useful spectral line corresponding to the excitation is defined as the number of measurement periods. The expressions applied to the current excitation I_{bat_alt} and to its voltage response V_{bat_alt} are as follows:

$$\begin{cases} \text{Re}(I_{bat_alt}) = \frac{2}{N} \sum_{n=0}^{N-1} I_{bat_alt}(n) \cdot \cos(2\pi kn/N) \\ \text{Im}(I_{bat_alt}) = -\frac{2}{N} \sum_{n=0}^{N-1} I_{bat_alt}(n) \cdot \sin(2\pi kn/N) \end{cases} \quad (5)$$

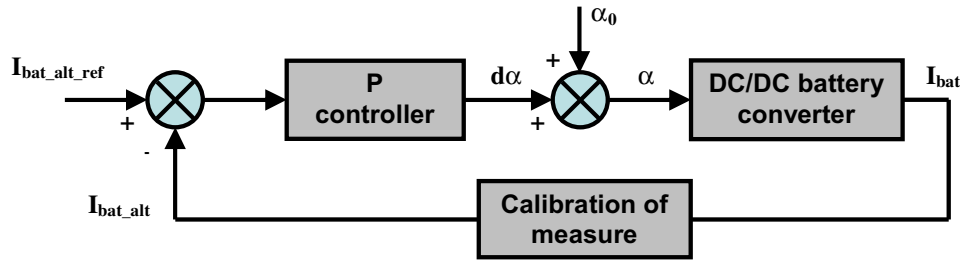


Fig. 9. Principle of excitation of the battery around an operating point.

$$\begin{cases} \text{Re}(V_{\text{bat.alt}}) = \frac{2}{N} \sum_{n=0}^{N-1} V_{\text{bat.alt}}(n) \cdot \cos(2\pi k_h n/N) \\ \text{Im}(V_{\text{bat.alt}}) = -\frac{2}{N} \sum_{n=0}^{N-1} V_{\text{bat.alt}}(n) \cdot \sin(2\pi k_h n/N) \end{cases} \quad (6)$$

The impedance is then deduced from complex expressions of current and voltage for the useful spectral line:

$$\begin{cases} \text{Re}(Z) = \frac{\text{Re}(V_{\text{bat.alt}}) \cdot \text{Re}(I_{\text{bat.alt}}) + \text{Im}(V_{\text{bat.alt}}) \cdot \text{Im}(I_{\text{bat.alt}})}{\text{Re}^2(I_{\text{bat.alt}}) + \text{Im}^2(I_{\text{bat.alt}})} \\ \text{Im}(Z) = \frac{\text{Re}(I_{\text{bat.alt}}) \cdot \text{Im}(V_{\text{bat.alt}}) - \text{Re}(V_{\text{bat.alt}}) \cdot \text{Im}(I_{\text{bat.alt}})}{\text{Re}^2(I_{\text{bat.alt}}) + \text{Im}^2(I_{\text{bat.alt}})} \end{cases} \quad (7)$$

6. Experimental results

6.1. Presentation of the experimental device

The experimental setup consists of a photovoltaic panel and a battery coupled to a DC capacitive network by their respective static converter. The wind generator is emulated by a power supply and power absorption by a programmable dynamic load. A

microcontroller as powerful as those widely available commercially was chosen to validate the possibility of implementing the algorithms on low cost devices. The converters are controlled by the DSP controller TMS320LF2407 from Texas Instruments clocked at 30 MHz. As shown in Fig. 12, the main internal peripherals that are used are the analog to digital converter which performs sampling measurements, PWM generators that perform the control of static converters, the SPI interface which performs control of the electronic calibration, and the SCI (Serial Communication Interface) which performs communications with external interface for data monitoring and storage (typically a computer). Control and battery impedance spectroscopy algorithms are implemented in this microcontroller.

The scale reduction factor of the battery, of solar panels and of the DC network voltage is selected to allow static converters to be used at the real elevation factor. The characteristics of the elements are as follows:

- Battery: VLRA AGM, 12 V 100 Ah
- PV: TE 850: $P_{\text{max}} = 85 \text{ W}$ ($V = 17.7 \text{ V}$, $I = 4.8 \text{ A}$, $T = 25^\circ \text{C}$), $V_0 = 22.2 \text{ V}$, $I_{\text{cc}} = 5.4 \text{ A}$
- IGBT modules of the converters: ARCEL FZ 400 R12 KS4 1200 V 400 A
- DC Network: Nominal voltage 40 V, Capacitance: 3300 μF

The semiconductor modules of static converters are associated with the DC capacitive network and a common heatsink as shown in Fig. 13. A fan provides forced air cooling of the power converters when necessary. These elements are over-sized to allow future tests with higher power (up to 30 kW). Validation of maximum power tracking and of energy storage management is presented in [13].

6.2. Validation of battery impedance spectroscopy

6.2.1. Sampling of calibrated measures

Fig. 14 shows sample results of the excitation current of the battery and the voltage response to the highest (1024 Hz) and lowest (0.32 Hz) excitation frequencies of the relevant spectral band. We can especially highlight the effectiveness of the calibration measurements in the digital range $[-511; 512]$ of the 10-bit ADC, and the effectiveness of filtering eliminating disturbances due to switching of the static converter. The amplitude of the excitation current is kept constant regardless its frequency. The amplitude and phase shift of the voltage response then depends on the value of the impedance at the excitation frequency regarded.

6.2.2. Impedance spectroscopy results

The online spectroscopy device is evaluated first on various known impedances to validate its operation. Fig. 15 shows the correlation between the representations in the Nyquist plot of the spectra obtained by the following three methods for a reference circuit: theoretical trace, offline measurement by a laboratory Zhaner IM6 spectrometer and measurement by the spectroscopy

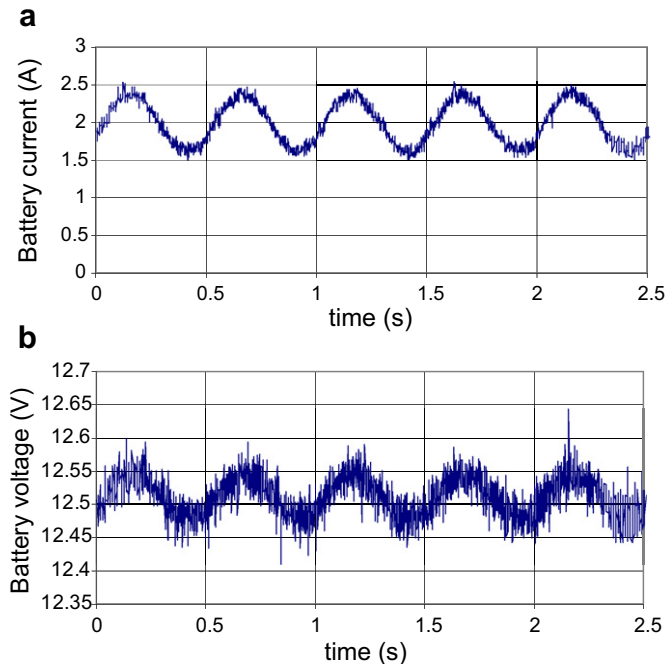


Fig. 10. Oscilloscope records of battery current and voltage with a 2 Hz current excitation ($I_0 = 2 \text{ A}$, $\Delta I = 0.4 \text{ A}$).

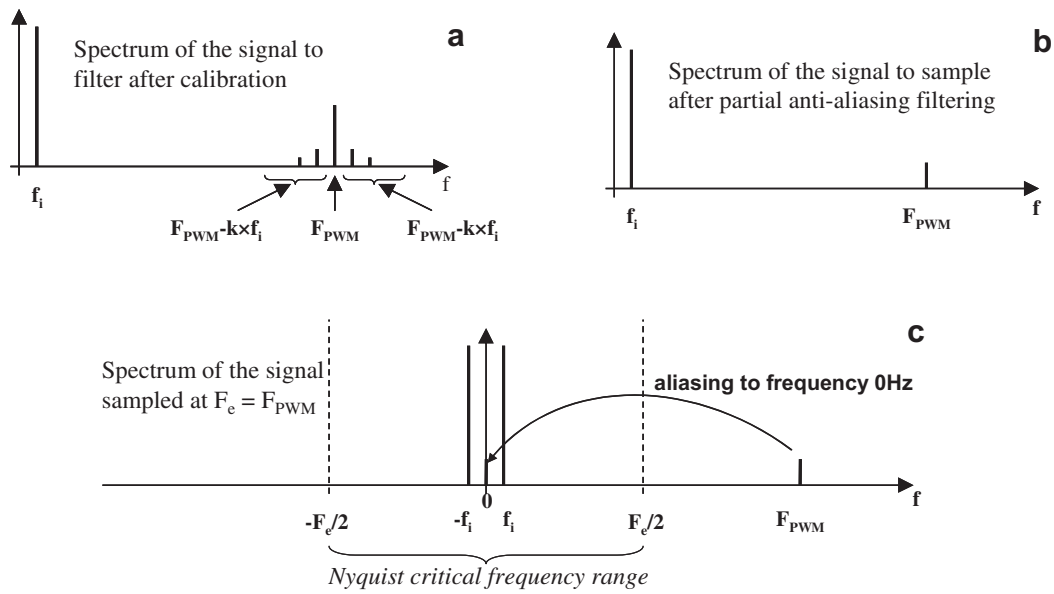


Fig. 11. Filtering and sampling analysis of battery current excitation and voltage response. (a) After calibration. (b) After partial anti-aliasing filtering. (c) After sampling.

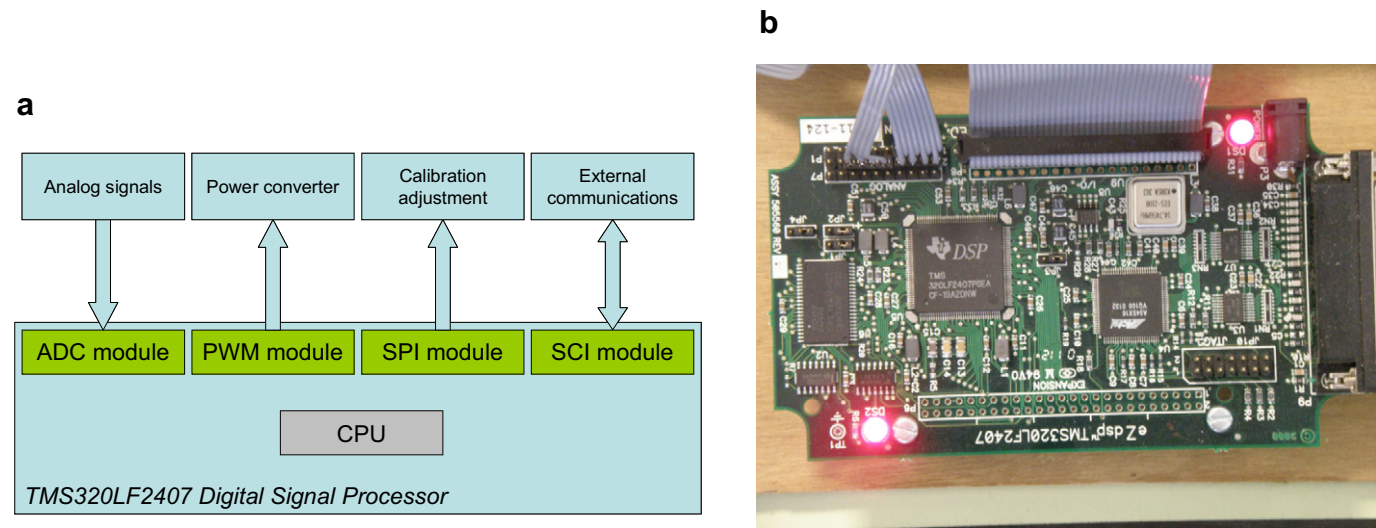


Fig. 12. Microcontroller platform. (a) Relevant functionalities. (b) Development board.

device integrated into the power converter. The reference circuit is made from resistive and capacitive components whose values are chosen to around those of the model of the battery used for the tests. The differences between the three curves obtained by these

three methods are small compared to the range of the impedance spectrum. The accuracy of the spectroscopy device by the power converter is therefore satisfactory. Furthermore, the observed differences take into account the possible variations of parasitic

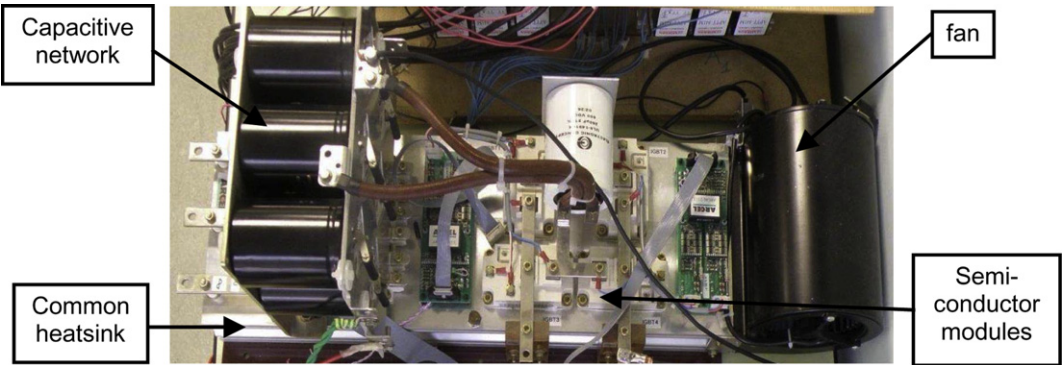


Fig. 13. Power converters and DC capacitive network.

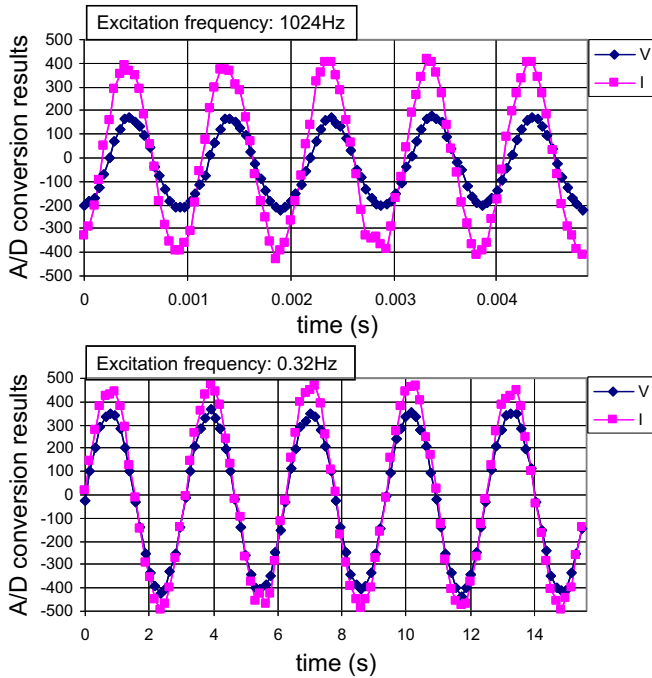


Fig. 14. Measures of excitation current (I) in the battery and of the voltage response (V) for two excitation frequencies.

impedances associated with the change of connection from one device to another, which are difficult to quantify.

Fig. 16a shows the Nyquist plots of online impedance spectroscopy obtained with the power converter at different moments of the battery charging by a constant current $I_0 = 1.2$ A. We observe the evolution of the plot of the impedance of the battery from which we can try to identify the evolution of the parameters of Randle model during the charging phase. Extrapolation of the high frequency area of each impedance spectrum which corresponds to the region to the charge transfer area allows their intersection point with the real part axis in $R_e + R_{ct}$ to be deduced. The evolution of extrapolated charge transfer resistance R_{ct} of the battery is shown in Fig. 16b. An example of exploitation of the measurements of online impedance spectroscopy would be to compare the evolution over time of the charge transfer resistance (Fig. 16b) and the terminal voltage of the battery represented Fig. 16c. The saturation

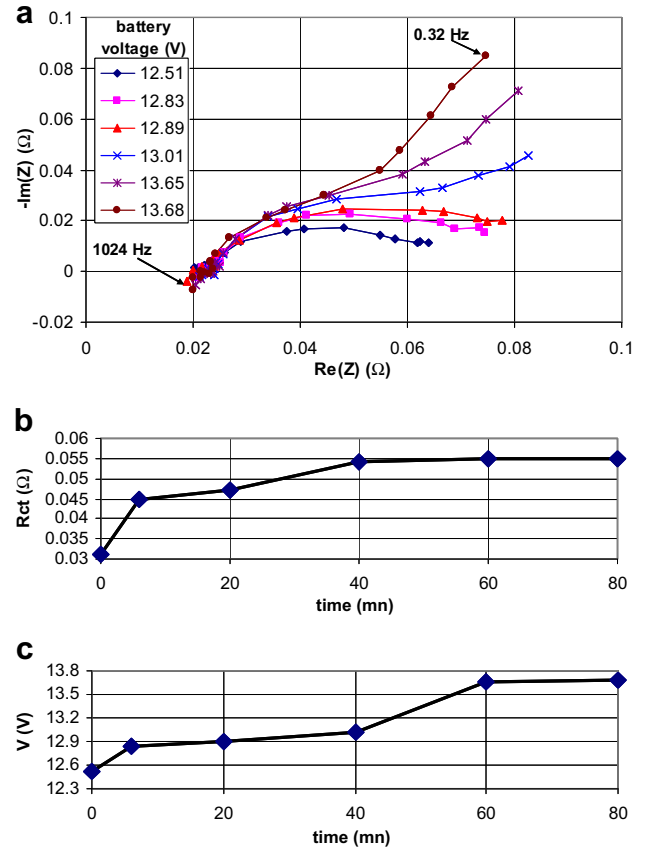


Fig. 16. Monitoring of impedance spectrum of the battery while charging at $I_0 = 1.2$ A. (a) Nyquist plot of impedance spectra. (b) Evolution of R_{ct} over time. (c) Evolution of the voltage V at the terminals of the battery over time.

of R_{ct} precedes the rapid growth of the terminal voltage of the battery which characterizes the gassing phenomenon of the battery.

Thus, the online impedance spectroscopy is used to evaluate the parameters of the equivalent model of the battery, and therefore provides information on its internal behavior. It is then easier to extract information more relevant and synchronous with the physical phenomena rather than from the observation of external parameters. This characterization method allows the relevant

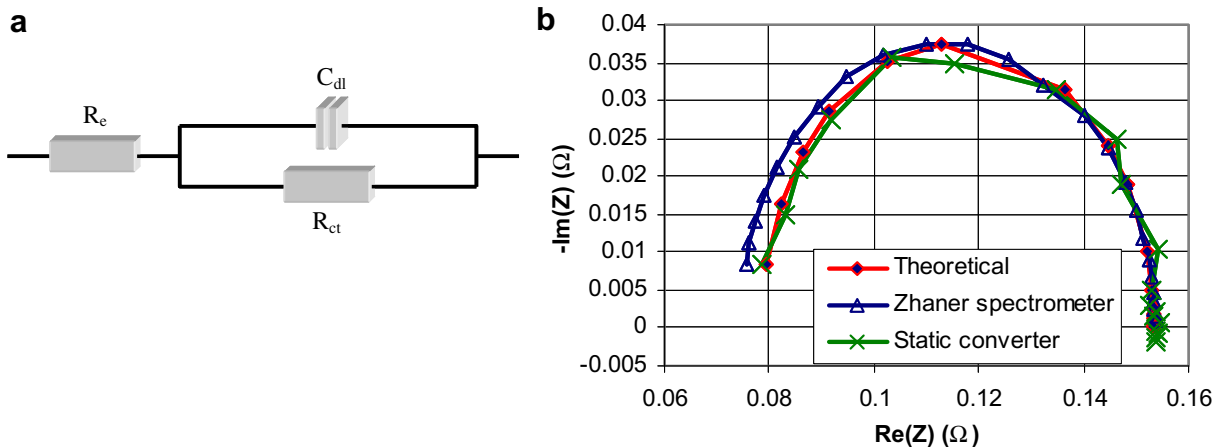


Fig. 15. Validation of online impedance spectroscopy with a reference circuit. (a) Reference circuit: $R_{ct} = 0.075$ Ω , $R_e = 0.08$ Ω , $C_{dl} = 0.018$ F. (b) Nyquist plots.

frequencies and the operating point to be chosen for convenience. However, the choice of very low frequencies has the effect of increasing the duration of the impedance spectroscopy.

The measurement of the internal parameters of the battery could be used to know the SoC and SoH of the battery. The study of the evolution of parameters over time would also help to know the influence of current profiles and of the temperature on the lifetime of the battery. Monitoring of battery parameters will improve their conditions of use and continuity of service of power plants, but it will also help reduce the cost of electricity. Monitoring of battery of electric and hybrid vehicles is a problem quite similar [14–16]. It will help reduce the cost and reliability of vehicle batteries.

7. Conclusion

This work contributes to the development of new methods of integration of advanced features in power conversion systems. Characterization of batteries by impedance spectroscopy using the power converter coupling the battery to the DC network has been validated in this paper. The principle of integration of impedance spectroscopy process presented in this paper allows the power transfer with the power converter not to be disturbed. Impedance spectroscopy of the batteries is achieved through the development of a calibration device which allows precise measurements and well-controlled excitation of the battery. The sampling principle described is used to filter the noise created by the power converter at the switching frequency. The complex impedance is computed using the DFT and the experimental results show real effectiveness of the device. The tests were first performed on a known reference impedance for validation and then on a lead acid battery while charging. This characterization method enables the monitoring of the internal parameters of batteries in actual operation and without additional hardware, thus at lower cost and lower size. Furthermore, it enables the battery impedance spectroscopy to be achieved automatically, at reproducible conditions and without external intervention or human help. This measurement strategy first presents the advantage to allow the knowledge of physicochemical processes of batteries in actual use to be enriched by exploiting

online spectroscopic records for a sufficient operating period. The identification of rules of correlation between these phenomena and the control profiles will then refine the methods of designing, sizing and control of hybrid systems constrained in cost and size in order to improve the lifetime of storage batteries.

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